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Research

A comparative appraisal of the resilience of marine social-ecological systems to mass mortalities of bivalves

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ABSTRACT. In many parts of the world, both wild and cultured populations of bivalves have been struck by mass mortality episodes because of climatic and anthropogenic stressors whose causes and consequences are not always clearly understood. Such outbreaks have resulted in a range of responses from the social (fishers or farmers) and governing systems. We analyzed six commercial bivalve industries affected by mass mortalities using I-ADApT, a decision support framework to assess the impacts and consequences of these perturbations on the natural, social, and governing systems, and the consequent responses of stakeholders to these events. We propose a multidimensional resilience framework to assess resilience along the natural, social, and governing axes and to compare adaptive responses and their likelihood of success. The social capital and governability of the local communities were key factors affecting the communities' resilience and adaptation to environmental changes, but the rapid degradation of natural ecosystems puts the bivalve industry under a growing threat. Bivalve mariculture and fishing industries are likely to experience increased frequency, severity, and prevalence of such mass mortality events if the resilience of the natural systems is not improved. An understanding of previous adaptation processes can inform strategies for building adaptive capacity to future events.

Key Words: *I-ADApT; mass mortality; response appraisal; shellfish*

INTRODUCTION

In the present Anthropocene era (Crutzen and Stoermer 2000), a key emerging concern is whether our social and governing systems are able to adapt to the new environmental conditions we are creating in the short and long terms, as well as locally and globally. How do they respond to stresses threatening environmental resources? Do their responses enhance or harm the resilience of the perturbed natural systems? A systems and resilience-based approach that considers the three systems together and the interactions between them is needed, rather than considering the systems individually or failing to consider the social and governing systems' actions entirely (Steffen et al. 2007, Folke at al. 2010).

Various terms are used in the literature to refer to what we call a "systems approach," including social-ecological systems (Berkes and Folke 1998, Folke et al. 2005, 2010, Berkes 2011, Perry et al. 2011), human-environment systems (Turner et al. 2003), and coupled human and natural systems approaches (Liu et al. 2007). Here, we recognize that the delineation between human and ecological systems is artificial and arbitrary (Berkes and Folke 1998) and that the relationship between humans and the environment is complex, bidirectional, and occurs at different but interrelated spatial and temporal scales.

The concept of resilience is helpful to describe the capacity of a social-ecological system to recover after a perturbation (Holling 1973, Walker and Salt 2006, Folke et al. 2010). This concept has to be understood in several dimensions (static and dynamic, ecological and social), which are not easy to disentangle, for example, in human-dominated systems such as shellfish farming. Resilience thinking also challenges conventional optimization and efficiency approaches applied to exploited ecological systems because the living world is changing and is configured by extreme events rather than average conditions (Walker and Salt 2006). Redundancies, often considered to be sources of inefficiency, can create resilience when a system faces external shocks and regime shifts (Biggs et al. 2012, 2015). We therefore hypothesize that social responses to ecological impacts are key factors of resilience and the degree to which bivalve systems can recover.

Here, we propose an assessment framework and develop a measure of resilience, focusing on mass mortalities of bivalves (MMB). These outputs contribute to the metrics of resilience and allow for international cross-case comparisons (Béné 2013), simplifying the complexity of concepts and processes at stake (Nemec et al. 2013, Quinlan et al. 2015), and identifying risks, opportunities, and alternate management strategies in marine systems (Resilience Alliance 2010). The multidimensional resilience framework (MRF) is able to capture, analyze, and assess responses within the natural, social, and governing systems. To test this framework, we use metrics based on responses to MMB gathered from six case studies of bivalve fisheries and farming systems using the "Assessment based on Description, Responses, and Appraisal for a Typology" (ADApT) approach developed by the Human Dimensions Working Group of the Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) program (Bundy et al. 2016). By applying the MRF to local case studies of environmental change and societal adaptation, we demonstrate the value of this approach to facilitate learning from other case studies presenting similar natural and social characteristics. Our approach is also used to illustrate how societies can cope with or adapt to adverse events that may ultimately be derived from altered biogeochemical cycles and interactions with local environmental stressors.

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REVIEW OF LITERATURE

The (long) history of mass mortalities of bivalves

Oysters, mussels, and clams are economically valuable, constitute significant sources of nutrition, and are part of cultural identities. In 2013, 15.3 million tonnes of marine bivalves were produced around the world (of which 89% was from aquaculture) for a primary value (ex-farm or ex-vessel) of $17.6 billion USD (FAO 2016). MMB events have been reported worldwide and have long been of particular concern, especially when the species supports a commercial fishery or plays a significant role in an ecosystem (Lafferty et al. 2004, Burdon et al. 2014). One of the first descriptions of an MMB outbreak dates to 1878, with the observation of bivalve diseases (Lafferty et al. 2004). Mass (or abnormal) mortalities of bivalve populations are generally defined as a loss of > 30% of the stock (Soletchnik et al. 2007, EFSA 2010). An increasing number of MMB outbreaks throughout the world has been reported since the 1960s (Imaï et al. 1965, Harvell et al. 1999, Lafferty et al. 2004, Soletchnik et al. 2007). This increase can be explained as a result of research progress on identification of diseases, the intensification of bivalve aquaculture, or may reflect changes in environmental conditions in production areas caused by climate change and water pollution.

Various causes have been identified for MMB outbreaks, including: high sea temperatures and heat waves (Cheney et al. 2000, Ortega et al. 2012, 2016, Rodrigues et al. 2015); changes in salinity (Xiao et al. 2005), turbidity, and pH; high primary production (Cheney et al. 2000, Mydlarz et al. 2006); eutrophic waters (Friedman and Hedrick 1991); invasive species as competitors or predators (Matsuyama 1999, McKindsey et al. 2007); pathogens (Elston et al. 1987); and density-dependent factors (Brazeiro and Defeo 1999, Xiao et al. 2005).

While a great deal of research has been devoted to the discovery of scientific causes behind MMB, the socioeconomic consequences of MMB events and the responses adopted by managers and growers or harvesters to cope with them have been described less frequently in the literature. Nevertheless, it is the study of these responses that is needed to guide efforts to minimize impacts and maximize recovery times. Have documented responses been successful at mitigating the outbreak or the effects of MMB on human communities, or not? What are the characteristics of successful responses? These are the questions that motivate our research.

Societal responses to mass mortalities of bivalves issues

MMB events have elicited a range of short-term and long-term responses among stakeholders and in governing and social systems, with dissimilar levels of success in restoring the system. These responses can be divided into two groups, technical and organizational, and they vary according to the production process, i.e., whether bivalves come from fisheries or farming systems. Technical measures primarily concern aquaculture systems, although operational management options (e.g., fishing gear selectivity) are also common for fisheries. Organizational measures can be applied to both wild-caught and farmed species. Fisheries and aquaculture must be envisaged as a continuum because enhancement programs may benefit both fishery systems, e.g., pollution reduction, and some farming systems that may also rely on wild-caught species (Anderson 2002).

Technical measures that have had some success include: (1) introduction of new or resistant species and varying the sources of spat to maintain the same level of economic activity (Grizel 1983, Grizel and Héral 1991, Ewart and Ford 1993, McKindsey et al. 2007, Padilla 2010, Castinel et al. 2015); (2) chemical or physical solutions such as water treatment, animal purification, immunostimulants, penicillin, active clay, hydrogen peroxide, and coagulants to prevent or limit disease (Di Salvo et al. 1978, Matsuyama 1999, Mydlarz et al. 2006); and (3) prevention measures such as monitoring and surveillance systems, quarantine and prevention of oyster movements to contain the disease, awareness and reporting by the industry, and risk assessment (Matsuyama 1999, Hine et al. 2001, Murray et al. 2012, Paul-Pont et al. 2014, Castinel et al. 2015). Organizational responses (e.g., state aid, mutual funds, diversification strategies, private insurance, inventories, and savings) occur at both individual and collective levels (Grizel 1983, Le Bihan et al. 2013, Lupo et al. 2014). These responses also take the form of changes in practices and management rules such as limiting effort, reducing bivalve density, going off the coast, changing the culture height in the water column, triage of dead oysters, and building cages against predation (Smith et al. 2000, Cassis et al. 2011, Pernet et al. 2011, Soletchnik et al. 2011).

These technical and organizational responses may also have potential negative and positive consequences in terms of "ecosystem engineering" (Padilla 2010). The introduction of new species such as *Crassostrea gigas* in many natural systems around the world has led to the introduction of pathogens or plankton attached to new imported species (Grizel and Héral 1991, McKindsey et al. 2007), but this has also created new substrates or three-dimensional habitats for other species, altered local hydrodynamics, and even changed the thermal environment through the radiant energy absorbed by their white shells on dark rocks (Padilla 2010). This one example illustrates that when assessing how well responses have worked, the objectives and stakes for the broader natural, social, and governing systems should be considered, raising new questions about the system's resilience to the initial MMB event and the responses by the human social systems.

METHODS

Definitions of resilience

The concept of resilience is useful to describe the capacity of a marine system to recover after a perturbation. Its origins are in ecology, where it was first introduced by Holling (1973) and defined by Walker et al. (2004) to describe "the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity and feedbacks." Pimm (1984) extended this concept to include "engineering resilience," a measure of the time it takes a system to return to "equilibrium" after disturbance. Resilience is now considered to include not only recovery but also resistance and reversibility (Palumbi et al. 2008). Resilience thinking has been extended beyond ecology and has been highly influential in systems approaches that integrate the social dimensions and interconnections between community well-being and ecosystems (Carpenter et al. 2001, Folke et al. 2002, Marshall et al. 2007). Folke et al. (2010) contend that that the concept of resilience should not be limited to ecosystem dynamics as traditionally understood. They argue rather for thinking of social-ecological resilience because "ecosystems and the social systems that use and depend upon them are inextricably linked" (Folke et al. 2010:2).

Here, we build upon operational definitions of resilience in a variety of domains (social, natural, and governing subsystems) to develop an MRF for MMB issues. Similar attempts have been undertaken in the past (Walker et al. 2004, Resilience Alliance 2010, Béné 2013, Nemec et al. 2013). Simplifying complex concepts without compromising the method's systemic and holistic approach remains an important challenge for resilience metrics (Walker and Salt 2006, Quinlan et al. 2015). Therefore, instead of reporting on every characteristic of resilience for both ecological and social systems, we assessed resilience through an equal weighting of the three (natural, social, and governing) systems rated along static and dynamic issues. Each of the six dimensions in our framework is characterized by a set of questions developed in the I-ADApT questionnaire and complemented by the scientific literature (Table C in Appendix 1).

Natural resilience

Natural or ecological resilience was assessed using two measures. The Holling resilience (H-resilience; Holling 1973) refers to the ability of an ecosystem to maintain its previous structure and function (i.e., the same biodiversity, trophic relationships, habitats, etc. before and after the shock). Systems were scored with a high H-resilience if the ecosystem maintained its state after a shock of a given magnitude, medium if there was partial maintenance, and low if the shock resulted in an altered state. Pimm's engineering resilience (P-resilience; Pimm 1984) was scored high if the speed of recovery after a shock was days to weeks, medium if recovery took several months, and low if recovery took several years or decades or did not occur. We also considered whether the natural (H- or P-) resilience is affected by the intensity of the shock because the speed of recovery relative to the shock itself also matters (Palumbi et al. 2008). Therefore, natural systems will be considered to be more resilient if their recovery is still possible after a severe perturbation.

Socioeconomic resilience

The communities involved in bivalve production systems are generally based on family-owned and small business units. From a social and economic point of view, resilience is defined as the ability of social systems to minimize welfare losses after a perturbation (Hallegate 2014). Socioeconomic resilience was described by two components analogous to H- and P-resilience (Rose 2004, 2007, Rose and Krausmann 2013): (1) Static socioeconomic resilience (S-resilience; Rose 2004) was defined as the ability of a system to maintain its functions (providing food, cultural value, employment, trade, profits, recreational use) when shocked, using the remaining resources as efficiently as possible during the course of recovery. S-resilience was considered high if the key indicators described above (e.g., output levels, employment, profits, cultural value) are fully preserved, medium if partially preserved, and low if the socioeconomic system is poorly preserved. (2) Dynamic socioeconomic resilience (D-resilience; Hertzler and Harris, *unpublished manuscript*) was measured by the speed of recovery after a shock, i.e., the expected time until a system switches from one system state to another. A disturbance can create opportunity for innovation, new activities, and development (Berkes et al. 2002, Gunderson and Holling 2002, Folke 2006), avoiding potentially dramatic social consequences. The ability to exit or to diversify and innovate may fall into this type of resilience. The D-resilience captured the speed of recovery, evaluated as high (several days or weeks), medium (several months), or low (several years).

Governing resilience

Governing resilience (G-resilience) was defined to represent decisions at the community or public policy levels to mitigate disruption to business after a perturbation (Kajitani and Tatano 2009). Four key attributes by which management of marine systems can successfully support resilience are: (1) embracing uncertainty and change (capacity for innovation and use of disturbances as opportunity); (2) building knowledge and understanding of resource and ecosystem dynamics; (3) developing management practices that measure, interpret, and respond to ecological feedback; and (4) supporting flexible institutions and social networks in multilevel governance systems (Hughes et al. 2005). These governing attributes were used to assess short-term G-resilience (STG-resilience) and long-term G-resilience (LTG-resilience). STG-resilience reflects the collective capacity to cope with disturbances with existing institutions (effective resource management with rapid and appropriate responses to a crisis situation). A Low STG-resilience score is associated with a lack of management institutions and collective organization, the absence of management rules, a protracted decision-making process (several months to years), or a mismatch of existing institutions and rules with the system to be governed (i.e., a scale problem between the drivers affecting the ecological system and the decision-making level). These make the system difficult to govern (Bavinck et al. 2013). Conversely, a higher STG-resilience score will be achieved if formal and informal rules play an important role in the governance of the marine system. LTG-resilience concerns the ability to reform the institutions and strengthen the adaptive capacity of the system in the long run by building new knowledge and practices in response to ecological feedback, creating social networks, reforming institutions toward flexible management committees and rules, solving conflicts, devolving social power, and raising funds to address the issue. A high LTG-resilience score is supported by a high level of research and development directed at the social ecological system, strong compliance with and participation of end-users in new management rules (e.g., comanagement), a multilevel governance system able to adjust the institutional response to the severity of external shocks, and the financial support by regional or national authorities to address the issue. A low LTG-resilience score is given if none of these efforts and changes are made, and a medium score if only part of this long-term investment is made.

Multidimensional resilience framework and index

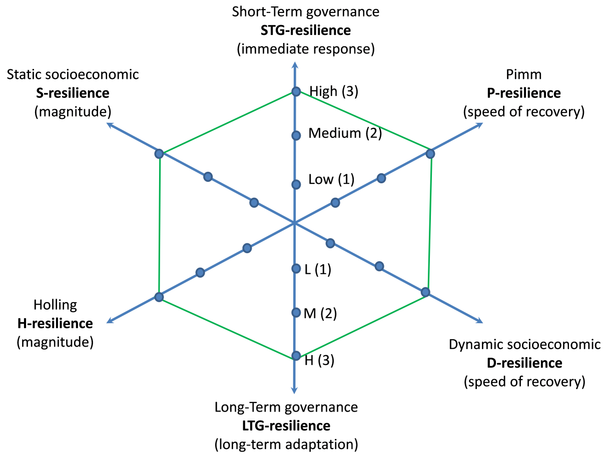
An appraisal framework of the responses implemented to cope with a critical issue such as MMB affecting the marine or coastal system was developed by combining all the dimensions of resilience (Fig. 1). The scoring for the six resilience axes of the MRF was based on information from the I-ADApT framework, which is designed to provide a rapid appraisal of responses to global change issues affecting local marine social-ecological systems by building on knowledge learned from past experience (Bundy et al. 2016). For each case study (Table 1), it includes: (1) descriptions of the natural, social, and governing systems, and responses by each to a perturbation; (2) appraisal of the responses;

Table 1. List of mass mortalities of bivalves case studies analysed.

Case study	Issue	Expert consulted
Matsushima Bay, Japan	Recent increase in norovirus-polluted oysters after the tsunami of 11 March 2011 and coincident with the increase in norovirus-affected patients in winter	Dr. Tetsuo (SEKI, Japan Fisheries Science and Technology Association)
Chesapeake Bay (Mouth of the Rappahannock River), USA	Appearance of the parasites known as MSX (*Haplosporidium nelsoni*) and Dermo (*Perkinsus marinus*), causing long-term declines in native oysters (*Crassotrea virginica*) in the 1960s	Professor George Santopietro (Radford University), Kurt Stephenson (Virginia Tech), and James Wesson (Virginia Marine Research Commission)
Puget Sound, Washington, USA	Poor harvests on the U.S. Pacific Northwest coast (Washington and Oregon coasts); decalcification and killing of oyster spat in hatcheries caused by acidification between 2005 and 2009	Professors Eddie Allison, Jack Cheney, and Ryan Kelly (University of Washington), and Sarah Cooley (Ocean Conservancy)
La Coronilla-Barra del Chuy, Rocha, Uruguay	Mass mortalities in the populations of yellow clam (*Mesodesma mactroides*) along its entire geographic range since 1994; the mass mortalities have been attributed to a number of factors, namely positive sea temperature anomalies, harmful algal blooms, environmental stress, artificial freshwater canal discharge, parasites, and storms	Professor Omar Defeo (Universidad de la Republica, Facultad de Ciencias)
Bay of Quiberon, Atlantic coast, France	Massive mortality and decreased growth of farmed oysters in summer 2006 because of local hypoxia near the bottom where oysters are cultivated	Dr. Joseph Mazurié (Ifremer, La Trinité-sur-Mer) and Véronique Le Bihan (PhD student at University of Nantes)
Bay of Bourgneuf, Atlantic coast, France	From summer 2008 onwards, mass mortality of oyster larvae and juveniles of farmed oysters (*Crassostrea gigas*) with very high mortality rates (between 40 and 100%) because of the presence of *oyster herpesvirus type 1* (OsHV-1) and *Vibrio* spp.	Patrice Guillotreau, Véronique Le Bihan, and Sophie Pardo (University of Nantes)

and (3) a typology showing emergent classes of similar response situations. A common case study template (http://www.imber.info) comprising 30 questions relating to the natural, social, and governing systems was designed to collect comparable information from case studies. A summary of the six completed MMB case studies' templates is included in Appendix 1 (Tables A and B). The I-ADApT templates were completed by experts with long-standing experience in their marine systems.

Fig. 1. The multidimensional resilience framework. The static dimensions are located on the left, and the dynamic dimensions on the right; short- and long-term governing resilience are located at the top and bottom, respectively. The green line depicts a system with a maximum level of resilience for every factor (= 3, or high), increasing the likelihood of successful responses.



From these responses, a scoring system for the six MRF dimensions (Table C in Appendix 1) was developed through a Delphi method (Dalkey and Helmer 1963). The final score was obtained by averaging independent choices made by the coauthors. Because interpretations of resilience criteria could sometimes give heterogeneous results, a Monte Carlo approach was used to draw randomly dimension values from a uniform law within the range of minimum and maximum values given by coauthors, and 500 trials of the MRI index were run for each case study, resulting in a distribution of the index value rather than a single average score.

On the basis of scores (valued between 1 and 3) for each axis, a resilience composite indicator, called the multidimensional resilience index (MRI) was computed for each social-ecological system by calculating the hexagonal area resulting from the six resilience measures. To calculate the polygon area, we first numbered the vertices in order (clockwise or counter-clockwise) starting at any vertex. Given that zero is the origin of the polygon, we consider two vectors a and b going from the origin to the first two vertices. The norm of the vectorial product $a \times b$ gives the area of a parallelogram passing symmetrically through the two vertices. The polygon area is given by the sum of all parallelogram areas and divided by 2. If we denote x_1 as the x coordinate of vertex 1, and y_n as the coordinate of the nth vertex, the area is given by the formula:

$$\left|\frac{(x_1y_2 - y_1x_2) + (x_2y_3 - y_2x_3) + \cdots + (x_ny_1 - y_nx_1)}{2}\right| \qquad (1)$$

The hexagonal area was then standardized over the maximum value if all dimensions had high scores (minimum area = 3; maximum area = 27). This results in an index of resilience standardized between 0 and 1 ([MRI − MRI_{min}]/[MRI_{max} − MRI_{min}]); the closer the index is to unity, the more resilient the system is. Despite potential criticism of a composite indicator (e.g., underlying assumptions regarding the substitutability and weights between the components; Klugman et al. 2011), it captures, in a snapshot, a complex and multidimensional reality and is often easier to understand for decision makers than is a bundle of separate indicators (OECD and JRC 2008).

RESULTS

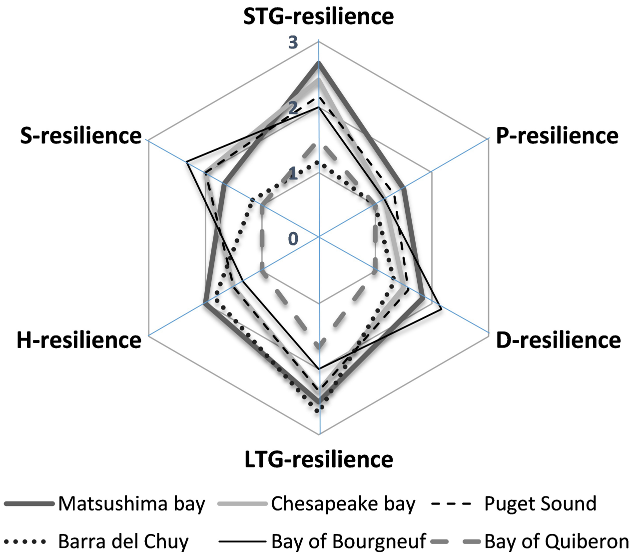
Overview of causes and responses

Causes of MMB in the six case studies include viruses, parasites, predators, hypoxia, acidification, algal blooms, freshwater discharge, and their various combinations. These proximate causes are not always the primary cause. Sewage discharges can result in virus outbreaks (e.g., Matsushima Bay after the March 2011 tsunami). Increasing temperatures and imports of exotic species result in opportunistic pathogens and predators (e.g., Bay of Quiberon, Bay of Bourgneuf, Chesapeake Bay). The combination of variation in localized upwelling of lower pH deep water and a rising trend in atmospheric CO_2 concentration that lowers global ocean pH result in ocean acidification (e.g., Puget Sound).

Given the diverse causes of MMB and their pathologies within the various ecosystems, the spatial effects (e.g., worldwide spread of *oyster herpesvirus type 1,* regional ocean acidification by upwelling water along the U.S. Pacific Northwest coast, local pollution in Japan), and production effects (from several to thousands of tonnes) should not be expected to be equivalent. The number of threatened jobs, for example, varied widely among the case studies (between 30 and 3000). In the U.S. Pacific Northwest, some bivalve farmers decided to leave the area, but for the most part, the industry in that case study has remained stable. In Matsushima Bay, the number of jobs has declined by 7% since 2011 (from 121 to 112). In Quiberon, a system hit by two sequential disasters (hypoxia in 2006 and pathogens since 2008), most of the oyster farmers have left the Bay (from 60 in 2005 to 10 several years after) to settle elsewhere (J. Mazurier, *personal communication*). In Barra del Chuy, the fishery was closed between 1993 and 2007, causing some fishers to move to other industries before the fishery reopened.

Despite this heterogeneous set of causes and consequences, common responses can be observed across the case studies (Fig. 2 and Table B in Appendix 1). In the Bay of Bourgneuf case, the H- and P-resilience are fairly low because monoculture resulted in a lack of biodiversity, although ecosystems can maintain their function with lower stocks of bivalves after an epizootic outbreak. S- and D-resilience are rather high because farmers proved able to adapt rapidly after every outbreak, in particular, by implementing substantial changes in practices (e.g., new species, new leaseholds for natural spat, more purchasing of triploid spat from hatcheries). However, S-resilience would have been severely reduced without important public funds. STG-resilience is rather low despite the multilevel governing structure (from national to regional management institutions). Collective action is poorly developed so that new management measures have been few and limited, although a ban on interbasin transfers of animals was implemented. The medium score of LTG governance is explained by the public efforts in support of research on the nature and causes of the virus outbreak, not by the industrial capacity of reforming institutions.

Fig. 2. The multidimensional resilience framework applied to six case studies of mass mortalities of bivalves. The polygons display the average resilience scores assigned by the coauthors and experts (1 = low, 2 = medium, 3= high) along six resilience axes for each case study.



In the case of MMB in the Bay of Quiberon case, all types of resilience are low, and no adaptive response was possible because of changes in natural characteristics within the Bay (i.e., hypoxia). The magnitude of the shock could be considered too high to sustain any kind of shellfish farming activity. Most farmers had to leave the Bay, with some able to stay in business by acquiring new leaseholds in other basins.

In Matsushima Bay, authorities were very responsive after the tsunami event, funding a substantial investment in sewage facilities, which included a norovirus inactivating function. Nonetheless, with long-term and uncertain effects for the industry, the S-resilience is rated as low. Farmers also adapted rapidly to the new situation but still suffered a dramatic decline in their income because of a fall in the value of shelled oysters due to norovirus infection.

In Barra del Chuy, the decision to close the fishery and the lack of mitigation measures by the government after the MMB led fishers to quit the yellow clam fishery (low S- and D-resilience). The natural system took almost two decades to recover after the MMB (low P-resilience) but is proving to be robust to shocks (H-resilience) as stricter management measures are taken (yellow clam population has been recovering gradually).

In Chesapeake Bay, the natural conditions make this system highly vulnerable to many threats, explaining weak H- and P-resilience levels. The emergence of pathogens dates back to the early 1960s, and the system has only started to recover recently after an ambitious replenishment program and management plan were implemented starting in 2000.

In Puget Sound, the industry and government undertook good short-term responses to cope with ocean acidification affecting oyster larvae, even at high costs (high S- and D-resilience).

The differences along the six axes were tested using mean difference t-tests at the 5% significance level. The test results isolate two case studies from the others: the Bay of Quiberon and Barra del Chuy. Concerning the STG scores, the null hypothesis of different means is accepted between these two cases and the four others. A similar result is found for the static economic resilience. For the other types of resilience, the results are not as clear. Note that this test of difference on means is not possible when experts are unanimous regarding the scores because the standard deviation is null.

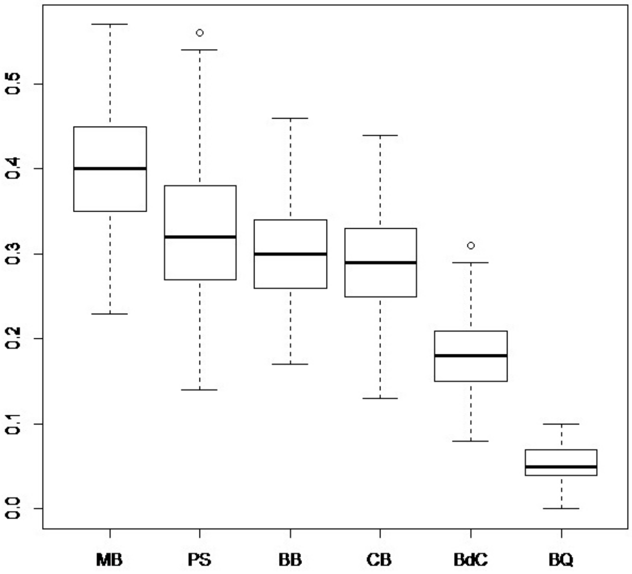
Appraisal of case study responses

The MRI was computed using a Monte Carlo approach: with 500 trials for each case study, the resilience scores of every dimension were randomly drawn and combined between the lowest and highest value proposed independently by the six coauthors. This procedure allows the uncertainty surrounding the scoring process to be considered. The ratio between the polygon area and the maximum area obtained if all dimensions had the highest 3-point score has also been preferred to an average resilience score across the six dimensions to emphasize the situations close to the critical levels of resilience. For instance, an average score of 2 (i.e., halfway between the minimum 1 and maximum 3 values) across the six dimensions would give a value of 0.5 using a simple arithmetic average index (halfway between 0 and 1), but only 0.375 using a standardized hexagonal area index.

The semiopen Bay of Quiberon has the lowest score (0.05) and the smallest range of uncertainty (50% of trials fell between 0.04 and 0.07), meaning that experts largely agree on the scoring (Fig. 3): the natural conditions have been degraded in the last few decades with less primary productivity and oxygen. In this bay, hydrological and weather conditions have changed (heat, northwest wind regime, local upwelling causing thermal stratification, declines in oxygen and phytoplankton), increasing the bivalve mortality risk. From 60 initial farms, only 10 are still producing in the bay. The average production has decreased from 220 tonnes/farm in 2005–2006 to 70 tonnes/farm in 2010–2011, along with a reduction in employment from 175 to 115 full-time equivalent jobs over the same period. No social or governing responses could sustain the oyster farming activity in such a poor environment.

In contrast, Matsushima Bay has the highest score (0.40), within a range of 0.35 (first quartile) to 0.45 (third quartile; Fig. 3). This relatively high score is mainly explained by the magnitude of short-term and long-term governance (adaptability) because the other dimensions of the MRF depict rather similar (or even lower) values to the other MMB cases. Several approaches have been found to inactivate norovirus in the short term, including heat treatment of shucked oysters. In the long term, the national government has invested massively ($42 million USD in 2013) in the reconstruction of sewage treatment facilities, which now have virus-inactivating functions. However, the number of farms has declined by 7% since 2011, and income levels have been halved because of low prices for heat-treated shucked oysters. Human health problems are solved in the short term, but norovirus is not eliminated, and consumption is therefore reduced, affecting the long-run profitability of farms. The average score for D-resilience has high uncertainty because half of the coauthors gave a low score (1) and the other half the highest one (3), suggesting that these estimates leave room for interpretation. This has been taken into consideration using the Monte Carlo approach.

Fig. 3. Box plots of the estimated multidimensional resilience index for six case studies of mass mortalities of bivalves. MB = Matsushita Bay, PS = Puget Sound, BB = Bay of Bourgneuf, CB = Chesapeake Bay, BdC = Barra del Chuy, BQ = Bay of Quiberon. The midline indicates the median, the box indicates the first and third quartiles of the distribution, whiskers indicate the minimum and maximum values, and circles represent outliers. All statistics are available in Appendix 1, Table D.



The remaining four marine bivalve systems are intermediate to these predecing two situations, with median scores of 0.32, 0.30, and 0.29, respectively, for Puget Sound, Bay of Bourgneuf, and Cheseapeake Bay, but a much lower score of 0.18 for Barra del Chuy, where the fishery was closed for 14 years (Fig. 3). For the first three systems, responses have been immediate and strong enough to cope with the socioeconomic issues in the short run, maintaining activity levels. However, issues are not solved in the long run, and the future of such systems is still under major threat.

In the Bay of Bourgneuf, the causes of MMB are still unknown, and some hypotheses (e.g., climate change, ocean acidification) are under investigation. No resistant species have been found despite various trials with imported oysters and local wild oysters. Bivalve production has been reduced by 30% since the virus outbreak, and many oyster producers who were close to retirement age or were weakly involved in this activity have left the industry. The remaining oyster farms were still facing very high mortality rates eight years after the beginning of the perturbation. The farmers were able to cope with this issue because of state financial compensation, increasing purchases of hatchery spat (particularly triploid seeds), higher market prices, and new practices (upper foreshore or deeper, new leaseholds to collect natural spat, diversification in other species such as mussels and algae).

In Chesapeake Bay, state intervention played a key role in the industrial recovery. A large-scale restoration program (Virginia Oyster Heritage Program) was initiated in 1999, and artificial reefs were built in 2001 with intensive shell replenishment (total cost of $2.4 million USD). The state also established a rotational ground opening scheme (with controlled season time and length, daily limits, and cull size set annually), created brood stock sanctuaries (no-take zones), and limited gear (only hand scrapes). The natural adaptive capacity of the system remains poor because of its high vulnerability to changes (presence of diseases such as MSX and Dermo, predation by whelks and rays, fresh water flow from storms, pollution levels, and sedimentation), which reduce the population size by approximately 50% per year. The large investment has nonetheless increased oyster populations on shelled grounds, achieving harvest levels in 2013 higher than those in the last 26 years. An undesired outcome of this success has been the increasing number of regulations violations (oystering at night, harvesting without a license, taking undersized oysters).

In Puget Sound, low-pH waters hinder calcification in shell-producing marine organisms. Under the Washington Shellfish Initiative, a temporary group, the Blue Ribbon Panel, was formed by gathering major stakeholders and was charged with suggesting management strategies to deal with the ocean acidification issue, with the assistance of a scientific group from the University of Washington. The Blue Ribbon Panel produced 42 policy recommendations and 18 key actions for reducing the effects of ocean acidification. This comprehensive study helped advocate for more fundraising, policy making, and awareness of ocean acidification-related issues. Technical measures have allowed farmers to cope with the ocean acidification problem by pumping higher-pH water and raising spat on shore at the larval stage before growing them in the open water. However, the industry expects that operating costs will continue to rise because of such changes in rearing practices.

In Barra del Chuy, ranked halfway between the previous group of three and the Bay of Quiberon, management authorities closed the yellow clam fishery from 1993 until 2007, almost immediately after the mass mortality outbreak (Ortega et al. 2016), but no options were provided to the fishers to mitigate the economic impact on their livelihoods. Consequently, fishers had to find alternative jobs in other industries (e.g., agriculture, construction). The natural system took almost two decades to recover after the MMB, but production is not back to pre-MMB levels. After the fishery reopened, in 2008–2009, a stricter comanagement system was implemented, with monthly total allowable catch, individual quotas, restricted numbers of licenses, minimum oyster size, closed season, and spatial measures. This fishery exhibits strong long-term governing resilience through a remarkable capacity to learn and adapt bolstered by the high level of scientific knowledge about this system.

DISCUSSION

Comparison of the resilience polygons across case studies gave insights into systems that may succeed in the future. The MRF results and tests of mean difference show at least two separate groups: Quiberon and Barra del Chuy, with lower scores; and Matsushima Bay, Bourgneuf Bay, Puget Sound and Chesapeake Bay, with higher scores. The main diverging dimensions concern the static economic and the short-term governance dimensions. STG resilience increases with the collective capacity to absorb shocks with existing institutions. In the case of mismatch between the governing system (with its existing institutions and rules) and the system to be governed (because of scale problems or areas of competence), the ability to address the issue is limited. In those case studies where the STG- and LTG-resilience reached higher scores, some of the responses involved compensation measures or restoration plans. In Europe, Japan, and the United States, several million dollars (USD) annually have been spent on national aid schemes to compensate farmers immediately after the crisis or to restore habitats. Projects have included shell replenishment of public grounds in Chesapeake Bay, the public Agriculture Calamity scheme and tax alleviation in France, and financial support from the local government to compensate insurance funds of fisheries cooperatives and subsidies to promote direct marketing in Japan. However, these efforts are not sufficient because the social response is missing some key principles of resilience (Biggs et al. 2015) such as maintaining diversity and redundancy, managing the slow variables and feedback effects (such as ocean acidification and pathogens), understanding social-ecological systems as complex adaptive systems, broadening participation, and promoting polycentric governance systems (where "polycentricity consists of multiple governing authorities that interact across different levels of the policy process" [Ostrom 2010]). Substantial financial effort to maintain the industry has not been adopted in Uruguay, a developing country that cannot afford such an expensive policy for a single and limited community; however, the reopening of the fishery after 14 years of closure has been marked by a complete change of management rules.

Changes in rules and practices were observed and found to be common in many case studies. Several management measures for fisheries and more technical measures for aquaculture were applied. Long-term responses dealing with slow variables were also forthcoming at many sites as prevention measures, including public awareness campaigns and development of early warning systems for ocean acidification, sanitary inspection systems, and monitoring systems for water and oyster quality. However, some other measures were more issue specific and localized, such as the introduction of new or resistant species, which is distinguished from a change in practices because of its unknown long-term consequences for the ecosystem (McKindsey et al. 2007, Padilla 2010). Similarly, chemical or physical solutions such as heat, filtration, or natural chemical treatment are only suitable in particular situations and are associated with much higher costs (water filtration or pH altering techniques, on-shore rearing techniques, better triage of dead bivalves, etc.).

The analysis of these case studies suggests that elongated hexagons prevail (Fig. 2), meaning that both short-term and long-term responses are effective but hardly cope with the issue in the long run because of the lower scores on other resilience dimensions. Most case studies refer to coastal temperate systems in shallow waters, which are highly transformed by intensive oyster monoculture. The natural system of bivalve farming in temperate shallow waters is perhaps not robust enough to absorb severe shocks (e.g., because of pollution or acidification, hence low H-resilience), but may recover rapidly if the social response is vigorous immediately following the perturbation event (e.g., construction of sewage facilities, hence relatively high P-resilience in the Matsushima case, or quarantine period). Biodiversity and the number of trophic levels are rather low in such human-made environments (McArthur 1955, McCann et al. 2000), particularly with frequent shocks such as disease, pollution, and heat waves affecting bivalve production (Glude 1975, Lafferty et al. 2004). This lack of diversity breaks the first principle of ecosystem resilience established by Biggs et al. (2012, 2015). It raises questions about the future of such monospecific culture systems facing new hazards. The recent degradation of natural conditions with increasing temperatures and ocean acidification has reduced the natural resilience of these coastal systems (Harvell et al. 1999, Cassis et al. 2011, Domeneghetti et al. 2014, Ekstrom et al. 2015). Ecosystems could deteriorate in the future because of increasing CO_2 and ocean acidification. Removing filter-feeding bivalves can result in an organic algae takeover, further altering water quality and the whole food web (Jokiel et al. 2008, Padilla 2010).

We showed that low natural resilience can be partly compensated by strong social innovation and protective governing systems (state aid, public research, replenishment plans), at least in the short and medium terms. Oyster farming social systems, sometimes created more than a century ago, proved to be resilient after several episodes of dramatic depletion (Grizel and Héral 1991, Ewart and Ford 1993, Renault 2011), but caused greater dependence on a single species (*C. gigas;* McKindsey et al. 2007, Padilla 2010) and hatchery technology (triploid seeds). Such a strategy has steadily reduced redundancies and diversity in the system, ignoring a key principle of social-ecological resilience (Walker and Salt 2006, 2012, Biggs et al. 2012, 2015). The periodic occurrence of crises in recent years, particularly since the proliferation of pathogen outbreaks in the late 20th century (Harvell et al. 1999, Matsuyama 1999, Cheney et al. 2000, EFSA 2010), reveals this weakness and puts the future of this industry in jeopardy.

CONCLUSION

We evaluated the responses provided by the social and governing systems to multiple issues causing MMB around the world. A systems approach was adopted that considers the linkages among the natural, social, and governing systems. We used two frameworks (I-ADApT and MRF) to collect and process data related to six MMB case studies. The concept of resilience was used analyze the capacity of marine systems to recover after severe external shocks along six dimensions: ecological, social, and governance, both in the short and long term. The developed MRF was particularly flexible and informative as an appraisal tool of responses, and the estimated MRI allowed us to compare the six MMB case studies with respect to their ability to recover after the shock.

Various responses across all case studies were able to save the industry in the short term in most cases, without restoring the long-term resilience of the natural coastal systems. The natural systems share common characteristics (poor biodiversity and biophysical conditions) and were degraded prior to the MMB events. The social and governing responses have been fairly creative and substantial, including technical innovations, preventive measures, management rules, financial aid, and support for public research. Although the responses succeeded in keeping the industries afloat in the short term, the underlying causes behind the MMB issues were often not discovered, and the sustainability of the social-ecological systems was not ensured in the long term. The presence of pathogens in at least three case studies (Chesapeake Bay, Bay of Bourgneuf, Bay of Quiberon) and the risk of ocean acidification in Puget Sound represent slow variables that are monitored but not fully understood, breaking at least two resilience principles defined by Biggs et al. (2012, 2015).

A resilient system ideally integrates both short- and long-term components. To prepare socioeconomic systems in advance of environmental change, general coping strategies could be developed with explicit current and future plans to be implemented stepwise in the event of a socioeconomic shock. To develop these integrated strategies so that they are effective for the social and ecological parts of the system, a range of stakeholders should be included and involved in an iterative process. At the same time, economic or risk-benefit scenarios could be developed that compare the effect of progressively enhancing resilience to ad-hoc responses carried out piecemeal, which can be costly or maladaptive. The case studies explored here show specific ways in which resilience can be enhanced to mitigate the consequences of MMB events. The analytical approach that we developed and demonstrated can be applied to identify weaknesses in the resilience of social-ecological system that need to be addressed.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/issues/responses.php/9084

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APPENDICES

1) Tables A and B: Application of I-ADApT to six Mass Mortality of Bivalves (MMB) case studies

2) Table C: List of resilience criteria used for the multidimensional resilience framework and indicator.

Table A	**Barra del Chuy** **Yellow clam (*M. mactroides*)**	**Puget Sound** **Oysters (*C. gigas*)**	**Bay of Bourgneuf** **Oysters (*C. Gigas*)**
STRESSORS	Freshwater discharge (since early 1980s) Increasing SST anomalies since early 1990s Cold winters 2007-08	Intensifying upwelling events of low-pH and high-CO2 water	Increase of SST (+1.5°C since 1970) and decrease of pH (-0.1 over the past century) High density of cultured stocks OsHV-1-mVar since 1991
NATURAL SYSTEM (change-impact)	Erosion and modification of the coastline (habitat) Reduced survival, growth and fecundity rates Mass mortality since 1993	Water conditions hostile to calcium carbonate minerals Massive larval mortality between 2005 and 2009.	Spillovers of spat Low yields Invasive species (*crepidula* and wild oysters) Massive larval mortality since 2008 (80-100%)
SOCIAL SYSTEM (change-impact)	Reduction of fishers' income and bankruptcies New jobs found in the construction and agriculture industries	Total of 3200 jobs endangered. Lower production (-21%; FAO: 2002-07/2008-11) 2 large hatcheries exporting oyster seed are facing high larval mortality rates	Triploid spat from hatcheries. Modified seasonal patterns of cultured stocks. Lower production (-30%) New costs from spillovers
GOVERNANCE SYSTEM (change-impact)	Weak governance: open access (1970s-1980s) Co-management system since 1990 Fishery closure 1993-2006 The fishery re-opened in 2008 with a precautionary approach	Lack of governance to address acute-onset change not driven by harvest levels. Creation of the Blue Ribbon Panel (scientists + growers + managers): action plan against ocean acidification and how to adapt	Lack of management measures to limit spat over-buying and production Restrictions on inter-basin transfers of oysters Technical measures on tables and meshbags

Table A	**Chesapeake Bay Oysters (*C. virginica*)**	**Matsushima Bay Oysters (*C. gigas*)**	**Bay of Quiberon Oysters (*C. Gigas*)**
STRESSORS	Presence of diseases (MSX and Dermo) and predation (whelks and rays) since 2002. Harvesting on the public grounds was low to zero by the mid-1990s.	An epidemic of Noro-virus food poisoning after 2011's tsunami because of destroyed sewage facilities.	Occasional hypoxia (more severe in 2006), near the bottom. Role of eutrophication not clear. Occasional toxic phytoplankton (Pseudo Nitzschia) and *OsHV1-µvar* since 2008.
NATURAL SYSTEM (change-impact)	Parasites appeared in the early 1960s which are salinity dependent so that the losses in oyster populations were greater toward the mouth of the Chesapeake Bay. Dead zones due to oxygen depletion have also grown since that time.	Lower productivity of oyster due to unsold oyster occupation at the farming system in the bay. In 2011, total seed oyster collection decreased to 40% of 2008. Remain production less than 20% level of the past average after 2011.	Changes in water quality (temperature, Oxygen, Phytoplankton), in growth rates and mortality risks. The invasive *Crepidula fornicate* is present at moderate densities.
SOCIAL SYSTEM (change-impact)	Population of 30,942 in the three counties, with a 36% increase from 1960 to 2010. 32 small-scale fishers.	Pop. 131,000 inhabitants. 112 oyster farmers in 2012 (-10% since 2003 and -7% since 2011). 15,082 inhabitants affected indirectly. Reduced revenue affects sustainability of oyster farming	60 small-scale oyster farms (of less than 10 jobs each). Decrease in the number of farms, economic vulnerability.
GOVERNANCE SYSTEM (change-impact)	Virginia Oyster Heritage Program initiated in 1999. Restoration of the public grounds at the mouth of the Rappahannock River by the Commonwealth of Virginia in 2000 (shell replenishment in public grounds). Partial funding has come from federal agencies.	Governor of Miyagi prefecture ask Miyagi Fisheries Cooperative best proper management of coastal water. Miyagi Fisheries Cooperative is responsible to manage coastal water production. In 2007, 31 independent Cooperatives have consolidated for cost-cutting purposes.	State intervention, industry representatives at the national (CNC) and local (CRC) levels. Scientific support by Ifremer. No particular change, except the access to public grounds.

Table B	**Uruguayan Yellow clam (*Mesodesma mactroides*)**	**US North Pacific Oysters (*C gigas*)**	**Bay of Bourgneuf oysters (*C. Gigas*)**
ADAPTIVE CAPACITY	Job opportunities in other sectors No financial aid to fishers. Important research activity on YC fishery for a long time. Co-management in force since 1990	Strong relationships between the industry, researchers, NGOs for solutions. Funds available to do the basic science. High levels of human resources in communities to address problem.	National funds to support affected farms (20 M€.yr^{-1} at the national level) Public research (causes and new virus-resistant species) No private insurance against disease No alternative virus-resistant oyster species
RESPONSES	Fishery closure 1993-2007 ; The fishery was re-opened under a co-management system in 2008/2009. a) monthly TAC; b) restricted nb of licenses (40); c) individual quotas; d) minimum clam size; e) only hand-gathering allowed f) spatial management g) harvesting season (summer)	Creation of plan for hatcheries to draw water in at specific times indicated by a warning system. Transfer of hatchery production to unaffected waters in Hawaii. Long-term research, monitoring plan through Blue Ribbon Panel. Genetic studies under way to identify resilient broodstock strain(s).	Restrictions on inter-basin transfers at the national level No new management measure implemented at the bay-level Individual responses: increasing number of spat collectors and hatchery seeds Offshore tech. experiments
APPRAISAL	The ecosystem is gradually recovering from overfishing and MMB, but not in line with pre-mass mortality levels, maintaining part-time jobs for fishers and less attractiveness for young people.	Short-term success: hatcheries still open, harvests & jobs preserved. Long-term outcomes still pending.	5 years after, high survival rate of farms despite the high larval mortality rates The causes of OsHV-1-mVar emergence since 2008 onwards still unknown

Table B	**Chesapeake Bay Oysters (*C. virginica*)**	**Matsushima Bay Oysters (*C. gigas*)**	**Bay of Quiberon Oysters (*C. Gigas*)**
ADAPTIVE CAPACITY	Very vulnerable to changes in fresh water flow from storms, pollution levels, sedimentation which reduces population by about 50% per year. Since the decline in the 1960s, alternative sources of income (other species) for fishers.	Changes of the bay environment caused by sudden Tsunami. Sanitary inspection system in every prefecture under government subsidies. Complete sterilization of the virus at the infestation site by public sanitary expert.	Scientific support (Ifremer) with a good monitoring system of water and oyster quality. Government support with intervention schemes (Agriculture Calamity scheme)
RESPONSES	A large scale restoration program was initiated in 2000: artificial reefs built in 2001 + intensive shelling (total cost of $2.4 M). The state established oyster harvest rotational grounds opening (season time and length, daily limit, cull size set annually). Gear limitation (only hand scrapes). Creation of brood stock sanctuaries (no-take zones)	Financial support from local government to compensate insurances of Cooperatives. New laws on food safety. Shucked oysters by heat treatment over 85 °C (Noro-virus is inactivated) but prices and incomes halved. Test application of various natural chemicals to inactivate Norovirus. Construction of sewage treatment facilities.	Government subsidies + tax alleviation Reduction in the number of farms (from 80 in the early 2000s to 10 in 2010).
APPRAISAL	Increased oyster population on shelled grounds. For entire state largest oyster harvest in 26 years in 2012-13. Increase number of violations of regulations including oystering at night, harvesting without a license, gathering undersized oysters.	Effective means for virus inactivation or useful technology to culture the virus have not been established yet.	Production of 15,000 t before 2006, half that level after.

TABLE C - List of criteria used in the multidimensional resilience analysis.

R-dimensions / definitions / references	**Criteria (I-ADApT questionnaire, literature)**
H-Resilience (Holling 1973 – static resilience of the natural system). The H-Resilience determines the persistence of relationships within a system and measures the ability of this system to absorb changes of state variables, driving variables, and parameters and still persists.	Q6. Prior to the main issue, what is the ecological status and habitat of the ecosystem at the ecosystem level (**L** if severely degraded; **M** moderately; **H** if not degraded)? Q7. What was the productivity of the system prior to the main issue (**L**ow, **M**edium or **H**igh)? →**H** if high productivity; **M** if moderate; **L** if low) (Palumbi *et al.* 2008). *Stability of the natural system (≠resilience) = variability around a state equilibrium. A system can be unstable but resilient (e.g. highly fluctuating climate conditions) and the other way around (in temperate systems not prepared to cope with climate shocks). →**H** if high fluctuations; **M** if moderate; **L** if stable) (Holling 1973).* *Probability of sustainable biomass (**H** if the biomass level is close to MSY; **M** if slightly beyond MSY; **L** if far beyond MSY).* *Same abundance and number of species, number of trophic levels and interspecific interactions (**H** if true, **M** if partially true, **L** if false).*
P-Resilience (Pimm 1984 – "how fast the variables return towards their equilibrium following a perturbation"	Q24ab. What were the results of the short term and the long term responses of the natural system? (**L** if negative or positive but take years, **M** if months, **H** if weeks or days). *Prior to the issue, did the natural system recover rapidly or not after an external shock? (**H** if rapid –few weeks to a couple of months-; **M** if moderate –few months to a couple of years-; **L** if slow recovery –years to decades).* *"Greater connectance drives community and ecosystem stability" (McArthur 1955). **H** if high connectance with weak interactions on average; **M** if medium; **L** if few, but strong connections* *Diversity-stability debate (McCann 2000). Multiplicity on the number of prey and predator reduces the dramatic changes of a population when one of the prey or predator declines in density (McArthur 1955). Most experiments show that "diversity is positively related to ecosystem stability" (McCann 2000, p. 230). "Ecosystem changes occur more quickly when ecological redundancy is low" (Palumbi et al. 2008, p. 36).* ***L** with only a few TL (1-2) and few species; **H** if great number of TL and species (e.g. 5 or more); **M** between these values.* *Persistence of the natural system = "the time a variable lasts before it is changed to a new value" (Pimm 1984). →**H** if the persistence of abundance and variety is high for years; **M** if it remains for a few weeks or months; **L** for a few days only.*
S-Resilience (Social and economic static resilience): ability of an economy to minimize welfare losses after	BI. Number of people affected by the Main Issue expressed as a ratio to the total number of people (**H** < 10%; 10 ≤ **M** < 20%; **L** ≥ 20). Q8. How many activities were impacted by the main issue? (**L** if more than

a disaster; "Reducing the consequences of failure and assuring business/service continuity under adverse conditions" (Rose 2004, 2007; Rose and Krausman 2013; Hallegate 2014). Economic resilience indices developed by Cutter et al. 2010; Bruneau et al. 2003; Jordan et al. 2011; Mayunga et al. 2007; Fisher et al. 2010 ; Norris 2011 ; Burton 2012; Rose 2009 (Rose and Krausman 2013, p. 79).	two activities severely impacted ; **M** if two; **H** if one only) Q9. Number of other livelihood opportunities? (**H** if more than two; **M** if one or two only; **L** if none) Q10. What % of the total catch/production is used for household consumption (not sold)? (**H** if less than 20%; 20% ≤ **M** < 60%; **L** ≥ 60%) Q11. What proportion of HH income comes from local sales of fish catches, processing, and wholesaling? (**H** if less than 20%; 20% ≤ **M** < 60%; **L** ≥ 60%) Q22. What were the short term responses of the social system to the main issue? (**L** if no response; **M** if one or two only; **H** if there are more than two responses). *State aid, insurance or any supporting emergency scheme at the local, regional, national or international levels (private insurance, mutual funds against natural disasters, tax policy, risk management plan, etc.) → **H** if the direct market and non-market costs –output losses, business interruptions, capital damages, casualties, lower demand…- are fully covered; **M** if they are partially covered; **L** if they are not covered at all).* *Profits, savings, access to loans of fishers-farmers-households to cope with a business interruption for a few weeks or months →**H** if amount equivalent to a 3 to 6-month activity; **M** if less than 3 months; **L** if none).* *Inventories, excess capacity, relocation, opportunities of input substitution, import substitution, (Rose and Krausman 2013) → **H** if large capacity; **M** if moderate; **L** if low.*
D-resilience ("ability to reconstruct and recover quickly", capacity to innovate, to diversify…); "capacity of innovation and use of disturbances as opportunity" (Berkes et al. 2003; Hughes et al. 2005; Hertzler and Harris 2010)	(Q11). Change of HH % income coming from local sales of fish catches, processing, and wholesaling? (**H** if the rate is lower or equal to -5%; **M** if the rate is negative and greater than -5%; **L** if no change) Q22. What were the long term responses of the social system to the main issue? (**L** if no response; **M** if one or two); **H** if three or more responses). *Degree of diversification. Capacity of fishers/farmers to turn to other marine productions or to alternative jobs. (**H** if more than two alternatives; **M** if one or two alternatives and **L** if none).* *Ability of fishers/farmers to innovate (proved in the past); → **H** = strong innovating capacity; **M** = moderate; **L** =poor* *Turnover of marine products over time –seasonally, from year to year…- (vs stability) →**H** if frequent turnover; **M** if moderate; **L** if stable and limited scope of goods.*
STG-Resilience (Short-term governance: Collective capacity to cope with disturbances with existing institutions) (Hughes et al. 2005; Charles 2007; Kajitani and Tatano 2009*).*	Q15. What are the key rules, regulations, instruments and measures employed to achieve the management objectives? (**L** if none, **M** if input or output measures alone, **H** if both input and output measures or formal co-management) Q16. Are there any informal rules, regulations, instruments and measures that play an important role in the governance of fisheries and aquaculture? (**L** if none, **M** if one or two, **H** if more than two). Q19. How concentrated is social power in the area? (on a 5-point scale: **L** if

	dispersion; **M** if moderately concentrated; **H** if concentrated) Q22. What were the short term responses of the governing system to the main issue? (**L** if no response; **M** if limited; **H** if variety of responses).
LTG-Resilience (Long-term governance: ability to reform existing institutions and strengthen the adaptive capacity of the system in the LR); "supporting flexible institutions and social networks in multi-level governance systems" (Hughes et al. 2005).	Q17. Nature of the relationship between occupations (conflict / cooperation on a 5-point scale)? (**L** if conflict; **H** if cooperation; **M** in-between) Q18. Who dominates or wields the most social power in the area? (**L** if very centralized –government-; **M** if devolved power to regional officers; **H** if very decentralized –fishers associations). Q20. Were there any structural changes in the governing system or individuals prior to the main issue? (**H** if large, **M** if some, **L** if no change). Q21. Were there any changes to the key rules, regulations, instruments and measures, or have any new ones been introduced prior to the main issue? (**L** if no change; **M** for several new rules; **H** of many new rules). Q22. What were the long term responses of the governing system to the main issue? (**L** if no response, **M** if limited, **H** of variety of responses). *Research-development capacity (number of researchers, facilities, national or regional funding schemes, quality of research measured by the number of publications on the issue, creation of panels, clusters,…) to cope with the issue (**H** for high capacity, **M** for medium and **L** for low capacity).* *Degree of compliance and acceptation of new rules and institutions (**H** for strong degree of compliance, **M** for moderately organized or **L** for individualism and non-organized behaviors).*

Legend:

BI = Background information in the I-ADApT questionnaire. All criteria with a Q(question) number are taken from the I-ADApT questionnaire (http://www.imber.info/Science/Working-Groups/Human-Dimensions/I-MBER-ADApT).

The variety and nature of answers given by experts in the I-ADApT framework and sometimes found in the literature are far richer (included in *italic* in the table). These answers can therefore be used to extend the list of criteria (e.g. research-development capacity related to the main issue, government financial support for the fishing/aquaculture industry, etc.).

TABLE D – Monte Carlo analysis of Multidimensional Resilience Index

(500 random trials - uniform distribution law)

	MB	PS	BB	CB	BdC	BQ
Mean	0.40	0.33	0.31	0.29	0.18	0.05
St. Dev.	0.07	0.08	0.06	0.06	0.04	0.02
Mean St. Error	0.00	0.00	0.00	0.00	0.00	0.00
Minimum	0.23	0.14	0.17	0.13	0.08	0.00
First Quartile	0.35	0.27	0.26	0.25	0.15	0.04
Median	**0.40**	**0.32**	**0.30**	**0.29**	**0.18**	**0.05**
Third Quartile	0.45	0.38	0.34	0.33	0.21	0.07
Maximum	0.57	0.56	0.46	0.44	0.31	0.10
Skewness	0.08	0.17	0.24	0.08	0.19	-0.06
Kurtosis	-0.65	-0.22	-0.33	-0.16	-0.41	-0.63

Legend: MB = Matsushima Bay, PS = Puget Sound, BB = Bay of Bourgneuf), CB = Chesapeake Bay, BdC = Barra del Chuy, BQ = Bay of Quiberon.

Interpretation: Skewness identifies how symmetrical the distribution is; a long tail to the right (left) has a positive (negative) skew. Kurtosis identifies how Gaussian the distribution is: a flatter (more peaked) distribution has a negative (positive) value.